

# Affordance++: allowing objects to communicate dynamic use

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## ABSTRACT

We propose extending the affordance of objects by allowing them to communicate *dynamic* use, such as (1) motion (e.g., spray can shakes when touched), (2) multi-step processes (e.g., spray can sprays only after shaking), and (3) behaviors that change over time (e.g., empty spray can does not allow spraying anymore). Rather than enhancing objects directly, however, we implement this concept by enhancing the user. We call this *affordance++*. By stimulating the user's arms using electrical muscle stimulation, our prototype allows objects not only to make the user actuate them, but also perform required movements while merely approaching the object, such as *not* to touch objects that do not “want” to be touched. In our user study, *affordance++* helped participants to successfully operate devices of poor natural affordance, such as a multi-functional slicer tool or a magnetic nail sweeper, and to stay away from cups filled with hot liquids.

**Keywords:** electrical muscle stimulation; affordance;

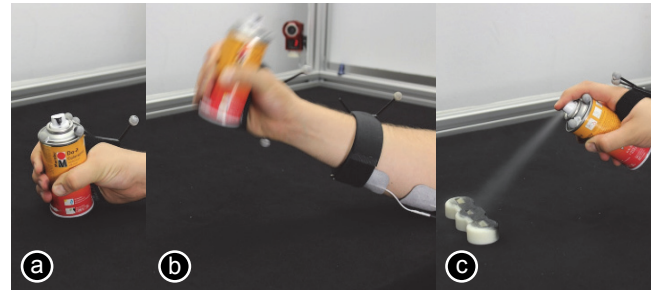
**ACM Classification:** H5.2 [Information interfaces and presentation]: User Interfaces: Input Devices and Strategies, Interaction Styles.

## INTRODUCTION

Affordance is a key concept in usability. When well-designed objects “suggest how to be used” [7], they avoid the necessity for training and enable walk-up use. Physical objects, for example, use their visual and tactile cues to suggest the possible range of usages to the user [7].

Unfortunately, physical objects are limited in that they cannot easily communicate use that involves (1) motion, (2) multi-step processes, and (3) behaviors that change over time. A spray can, for example, is subject to all three limitations: (1) it needs to be shaken before use, but cannot communicate the shaking, (2) it cannot communicate that the shaking has to happen before spraying, and (3) once the spray can is empty, it has no way of showing that it cannot

be used for spraying anymore (and instead should now be thrown away).



**Figure 1: Affordance++ expands the affordance of an object beyond its visual attributes. (a) This spray can needs to be shaken before use. (b) Affordance++ allows the spray can to make the user shake it before use. Our prototype implements this by electrically stimulating the user's muscles. (c) Now the spray can is “willing” to be used.**

As pointed out by Djajadiningrat et al., the underlying limitation of this type of physical object is that they cannot depict *time* [3]. The spray can is inanimate. Motion, multi-step processes, and behaviors that change over time, however, are phenomena in time.

One way of addressing the issue is to provide objects with the ability to display instructions, e.g., using a spatial augmented reality display [20]. To offer a more “direct” way for objects to communicate their use, researchers have embedded sensors and actuators into objects, allowing them to be animated [21,25]. This approach works, unfortunately, at the expense of substantial per-object implementation effort.

In this paper, we propose a different perspective. While animating objects allows implementing object behavior, we argue that affordance is about implementing *user behavior*. The reason is that some of the qualities of an object are not in how the object behaves, but in how the user behaves when making contact with the object.

A good part of the process of communicating how the user is supposed to operate the object, however, takes place before users even touch the object. Users operating a door handle do not just touch the handle to then re-adjust their hand position based on the handle's tactile properties; rather, the object communicates its use while the user's hand is approaching it. The haptic quality of the handle itself ultimately does play a role, but by the time the hand reaches the door handle, the user's hand is already posed correctly to grip the handle.

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In this paper, we therefore propose creating object behavior by controlling *user* behavior. We achieve this by instrumenting the user, rather than the object. This allows us to implement object behavior not by providing objects with the ability to respond to the user, but by re-creating how the object wants the user to respond to the object.

### AFFORDANCE++

We call this concept of creating object behavior by controlling *user* behavior *affordance++*.

Conceptually there are many ways of implementing *affordance++*, generally by applying sensors and actuators to the user's body, such as the arm. In this paper, we actuate users by controlling their arm poses using electrical muscle stimulation, i.e., users wear a device on their arm that talks to the user's muscles by means of electrodes attached to the user's arm (we describe the device in detail in section "Prototype"). This allows for a particularly compact form factor [14] and is arguably even more "direct" than the indirection through a mechanical system. However, the concept of *affordance++* needs not to be tied to a particular means of actuating the user, but to the concept of doing so instead of actuating the objects that the user interacts with.

Figure 1 illustrates *affordance++* at the example of the aforementioned spray can. *Affordance++* allows the spray can to produce a range of different types of behavior. In the shown example, when the user grasps the spray can, the spray can causes the user to shake it. Our prototype implements this either using an optical tracking system or using a sensor in the user-worn device that recognizes a marker inside the spray can. Once recognized, the prototype plays back the desired behavior into the user's muscles.

As we illustrate in the following section, *affordance++* allows objects to produce multiple types of behaviors, including behaviors that start prior to physical contact. By storing information about objects' states, *affordance++* allows implementing not only motion, but also multi-step processes and behaviors that change over time.

On a technological level, the electrical muscle stimulation technology we use is able to *make* users perform certain motions. However, *affordance++* intentionally avoids this and instead *suggests* how to use objects by actuating the user's hand with low intensity. This keeps users in the loop, allowing them to decide when to follow a suggestion and when to overwrite it.

### EXAMPLES OF USE

We now demonstrate the expressiveness of *affordance++* at the example of six unfamiliar household objects and tools. All six of them we examine further in our user study. We cluster examples by the key features of *affordance++*.

#### (1) Motion: where to push the lamp?

In Figure 2, *affordance++* helps users operate a lamp of a rather abstract design [1]. (a) Here the user's hand approaches the lamp from the left side. (b) The object responds by gently pushing the user's hand towards the right, (c) where it flexes the hand gently to suggest pushing down. This tips the lamp over, (d) turning it on. In the same manner,

when approaching the lamp while it is on, *affordance++* moves the user's hand to the side and pushes it down to turn the lamp off.

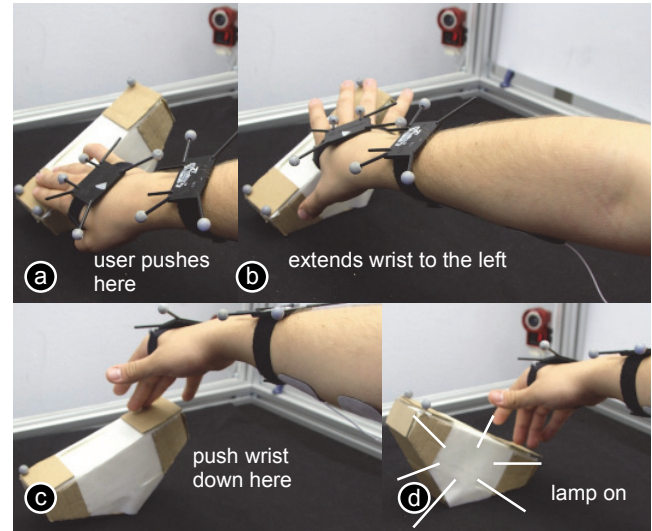


Figure 2: Here, *affordance++* helps the user interact with an unfamiliar lamp.

#### (2) Multi-step processes: Magnetic Sweeper & Slicer

In Figure 3, *affordance++* helps users handle an unfamiliar object. This "nail sweeper" allows users to pick up and drop objects with the help of a magnet—an example of a multi-step process. (a) The tool suggests grasping the handle by repelling the user's hand when trying to grasp any other part. (b) Afterwards the device suggests sweeping the nails by slowly rocking the wrist back and forth.

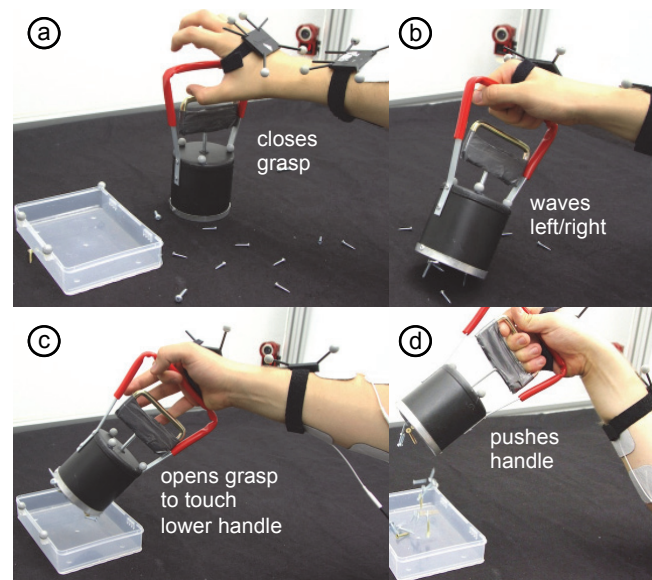


Figure 3: The magnetic sweeper is an example of an unfamiliar tool that requires a correct order of execution.

The critical moment occurs when collecting a screw. Here users typically reach for the lever below the handle, as they assume this is how one *collects* the screws. This assumption is, however, false and *affordance++* repels the user's hand



from grasping this handle and continues the sweeping motion. (c) Only when the user hovers over the container, affordance++ loosens the user's closed fist, allowing the user to grasp the lever and (d) by pulling the lever, the magnet releases the screws.

The next example, depicted in Figure 4, shows a patented kitchen tool with multiple functionalities. The challenge here is to find out what each part does and when to use it. (a) The user explores the unfamiliar tool and tries to grasp it. Here, affordance++ repels from grasping the knife blade and only affords grasping the other end. (b) After grasping, affordance++ suggests cutting with the blade, by gently rocking the wrist back and forth.

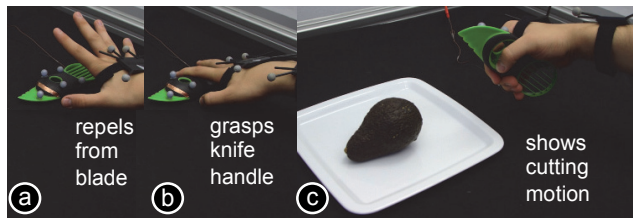


Figure 4: Cutting the avocado in half with this tool.

The next step is to remove the pit from the avocado, shown in Figure 5. This kitchen tool affords this by providing a set of blades inside a hole that extract the pit. (a) Affordance++ repels the user from removing the pit with the knife tip and (b) waves the tool back and forth parallel to the pit. This suggests a slamming motion, which the user performs in order to extract the pit.

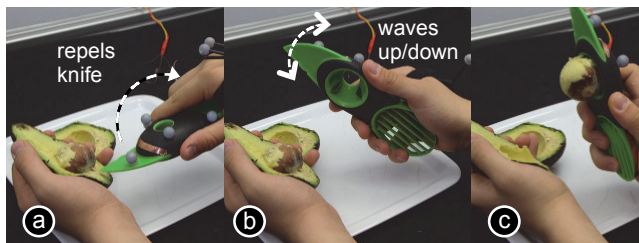


Figure 5: Extracting the pit using the tool.

The last step is to slice the avocado in pieces. While the conventional way is to peel off the skin and then slice each piece individually with a knife, this tool does it in one step. However, as we found in our user study, this instruction is not easily discoverable. Affordance++ helps here by (a) releasing the grasp gently as to suggest grasping the other end and (b) moves the tool towards the avocado suggesting a scooping motion. (c) Users respond by performing the scoop, which slices the avocado simultaneously.

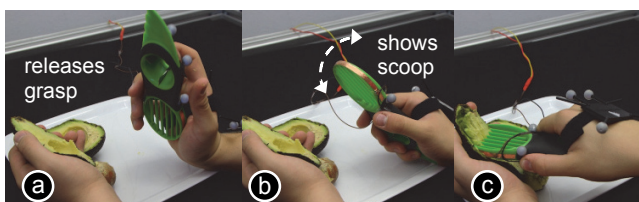


Figure 6: This tool allows for slicing the avocado without peeling the skin.

### (3) Behaviors that change over time, e.g., the hot cup.

The same mechanism applies to familiar objects for which the current state is unknown because object properties change over time. Figure 7 depicts how affordance++ supports a change in an object's property—here, temperature. (a) The user is trying to grasp the cup around its body while pouring hot tea. Albeit the object's typical affordance (i.e., round and small—affording grasping) this is a case in which the affordance needs re-adjustment. (b) Affordance++ now repels the user by over-extending the palm as to prevent grasping around the body, and (c) affords grasping only around the handle, by making the user thumb flex inwards into a pinch gesture.

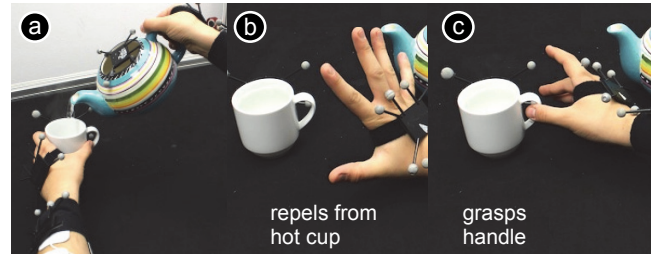


Figure 7: Changing behavior according to the object's state: (a) this cold cup affords grasping, (b) when hot it repels the user's hand, but (c) its handle continues to afford grasping.

Figure 8 shows a door that changes its behavior in accordance to what happens behind the door. The user approaches a door handle, ready to open it. (a) The room is busy however, as a meeting is taking place inside. The handle therefore repels the user's hand preventing it from grasping the handle and instead (b) suggests knocking by closing the user's fist and (c) rocking the wrist back and forth. The user (d) decides to knock by approaching the door's surface with the hand.

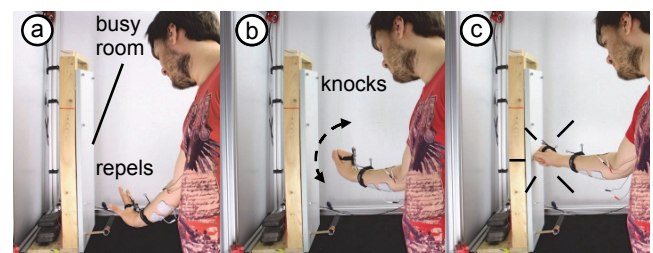
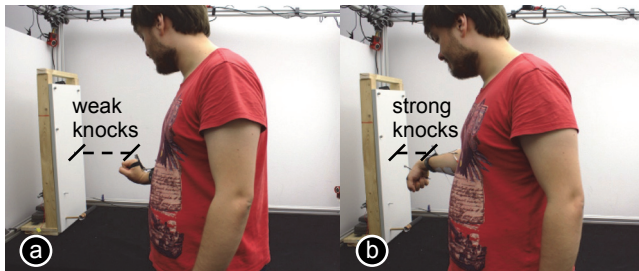


Figure 8: (a) When approaching the door handle, (b) it repels the user's hand because someone is inside. (c) The system suggests that the user knocks by actively curling his fingers into a fist and knocking in the vicinity of the door's surface. The user opts to knock by approaching the door with the hand.

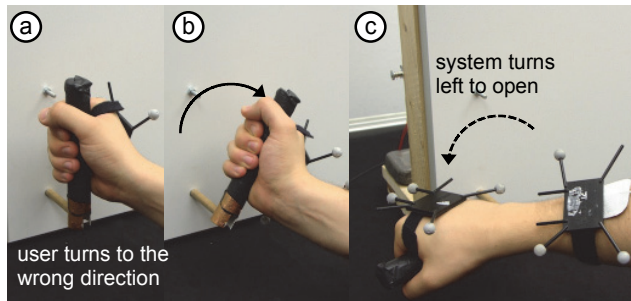
This “knocking example” is what we call a *preemptive demonstration* of how to operate the object. Figure 9 extends this concept further. Here, the door communicates with the user at different distances. At 75 cm, users feel their hand closing into a fist. (b) At 50 cm users feel their hand starting a gentle knocking pattern. Lastly, (d) at about 25 cm the knocking pattern becomes stronger. This is an example of attaching an envelope to an object. Here, the envelope maps to the amplitude of the knocking gesture. Another design is

to affect frequency, i.e., the closer the user gets, the faster the knocking becomes.



**Figure 9:** While approaching a door with the intention to knock, *affordance++* allows the gesture amplitude to be communicated as a function of distance from user to object.

In Figure 10, the user is trying to open a door. When grasping the handle, *affordance++* suggests turning left and prevents the user from turning the wrong way. *Affordance++* is helpful here, because the mechanism is not visible to the user, which is the case for most push/pull doors [4].



**Figure 10:** Overwriting the user's intention by providing the right turning direction.

Likewise, this example can be done at a distance with preemptive demonstration. While approaching a door's handle, *affordance++* demonstrates the turning left/right (or pulling/pushing) prior to contact with the object.

### CONTRIBUTION

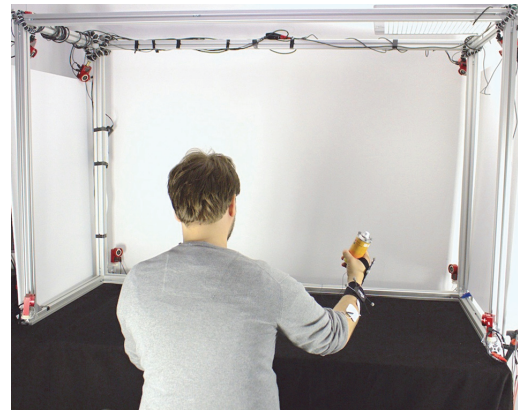
Our main contribution is that we extend the notion of affordance so as to include dynamic object behavior. We thereby allow objects to communicate motion, multi-step processes, and dynamically changing behavior. *Affordance++* allows objects to *communicate* dynamic use to users, but at the same time keeps users in the loop, allowing them to overwrite objects' suggestions. A key property of *affordance++* is that it allows objects to affect users *before* they make physical contact with the object. We demonstrate a simple prototype that accomplishes this by actuating the user using electrical muscle stimulation. We validate our concept in a user study.

On the flipside, *Affordance++* is subject to several limitations. (1) Our muscle-based implementation is low bandwidth limiting us to simple poses and simple behaviors. Also, any solution based on electrical muscle stimulation requires recalibration once the muscles fatigue over time [9]. (2) Our implementations are just simple prototypes to illustrate the concept. Future versions should integrate more

elaborate tracking solutions, e.g., based on mobile optical tracking (e.g., Digits [10]).

### PROTOTYPES

Figure 11 shows the simple prototype setup we used to explore the concept of *Affordance++*. It uses electrical muscle stimulation, which provides us with a particularly direct way of instrumenting users. The tracking component of the shown version is based on optical motion capture.



**Figure 11:** This *Affordance++* prototype uses an 8-camera *Optitrack* setup for tracking. The user wears rigid body markers on the hand and on the forearm. Also objects, such as the spray can shown here, are tracked using markers.

### Electrical muscle stimulation

Our prototype implements object behaviors by actuating the users' muscles using a computer-controlled electrical stimulation unit. The unit is comprised of 4 individually addressable channels. The unit allows for safe operation by limiting the output current to 100mA. The pulse-width (150 $\mu$ s-250 $\mu$ s) and frequency (80-140Hz) are variable and calibrated per-user, per-channel and remain fixed once calibrated. Intensity is regulated on the fly using an *Intersil X9C102* digital potentiometer that addresses the voltage-controlled amplifiers. A microcontroller (*ATMEGA328*) steps the digital potentiometer up/down on request by the *affordance++* software. The latency of a one-step change is around 1ms, which makes the latency of a minimum-to-maximum actuation sweep (calibrated per user for pain-free operation) less than 100ms. Depending on the pose and on the user's skin resistance [2], the object uses a different waveform configuration (frequency and minimum and maximum amplitudes), which is sent to the microcontroller and which then regulates the output current.

### Muscles actuated

Figure 12 depicts all the poses we use in *affordance++* and the muscles actuated for each pose: *squeeze*, *turn*, *repel*, *drop*, *shake* and *raise*. Each action uses at most four electrodes. Complex actions are achieved by combining these actions, for instance, "knock on a door" is composed of *squeeze* for a closed fist and *shake* for a knocking motion.

### Tracking and how it triggers object behavior

The prototype triggers object behavior when it detects certain spatial relationships between the user's hand and one or



more tracked objects. It computes this by surrounding objects and hands with collider objects (Figure 13). When the user's hand intersects with an object's collider, it triggers the respective object behavior. By using colliders of different sizes, behaviors may be triggered closer or further.

The prototype allows triggering object behaviors based on the hands proximity to the object, as well as when the user is reaching for the object. The prototype computes the latter by extrapolating the hand's trajectory using a ray it casts in the direction of the hand's motion. It determines the direction of motion based on the moving average of the past hand positions (from the last 50ms = 20 frames).

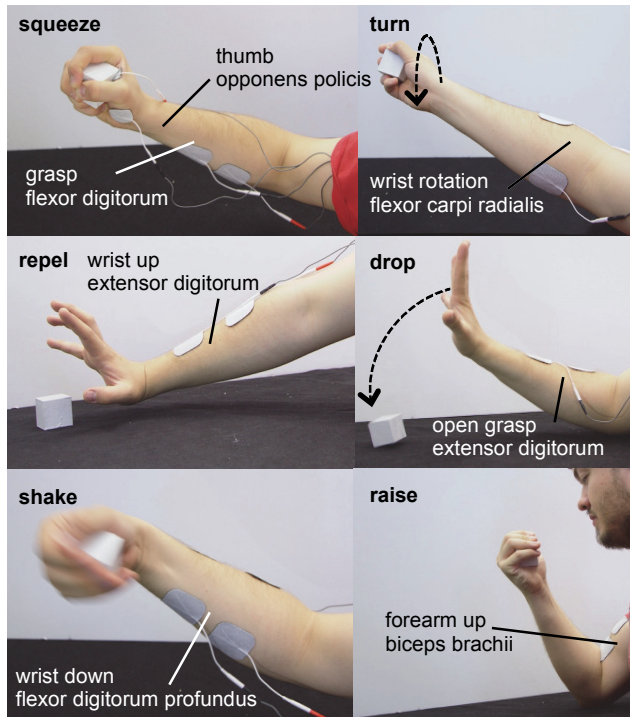


Figure 12: Electrodes for each gesture used in Affordance++.

Furthermore, this prototype provides users with two strategies to dismiss an ongoing object behavior. First, by removing their hand from the collider volume. Secondly, if the ongoing behavior involves motion (such as knocking the door) or in the case of handheld objects (e.g., spray can) users may also dismiss it simply by resisting the motion.

Our prototype implements these mechanisms and behaviors based on the Unity3D engine.

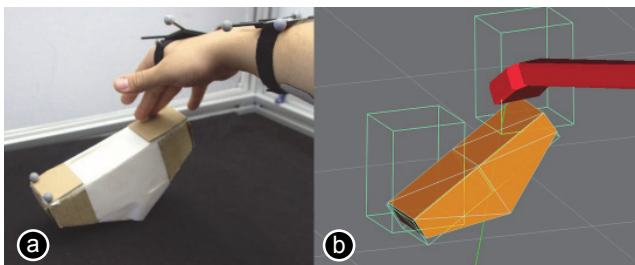


Figure 13: (a) Here the user approaches the designer lamp. (b) In Unity3D, we detect the collision with the bounding volumes and trigger the pulling down gesture.

This prototype works reliably, but it is obviously limited to the size of the shown workspace and subject to occlusion.

### Mobile RFID-based tracking

To allow us to explore mobile use, we created a second prototype. Although limited to interactions that can be expressed with proximity using RFID, it allows us to prototype some of the examples presented earlier, such as the door in Figure 8, by placing an RFID tag on the handle.

As illustrated by Figure 14, the prototype contains all electronics attached to a sleeve. It features a 2-channel version of our aforementioned computer-controlled muscle stimulator, which it controls using digital potentiometers controlled by an *ATMEGA328* microcontroller, which sits behind the RFID antenna. The prototype contains the SM130 Mifare 10MHz reader and objects contain passive tags.

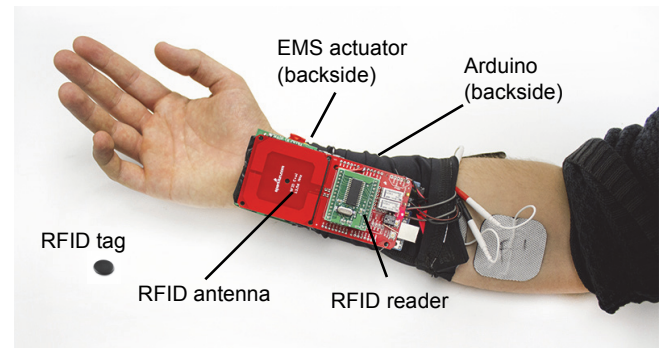


Figure 14: Wearable prototype based on RFID

### USER STUDY

In order to validate the concept of affordance++, we conducted a user study.

The objective of Task 1 was to verify that affordance++ indeed allows communicating identifiable object behaviors. For this purpose, we had participants touch blank generic objects that played back different types of behaviors. Participants responded by naming the behavior they felt the object was performing.

The objective of Task 2 was to verify that affordance++ indeed allows objects to communicate use. We had participants operate six objects that attempted to communicate their non-obvious use through affordance++.

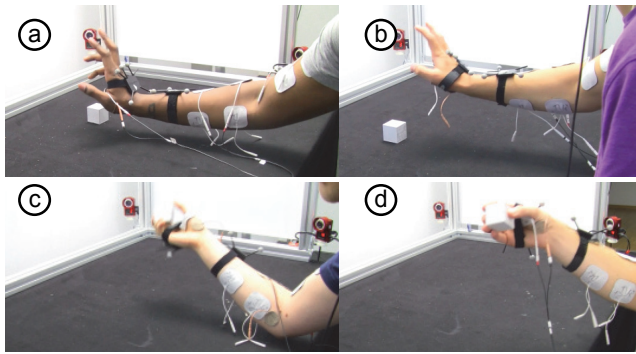
In the interest of clarity, we present procedures and results grouped by task.

#### Task 1: understanding the meaning of induced motion

Each participant received the same blank, generic white cube shown in Figure 12, which we provided with one of six affordance++ behaviors: *repel*, *drop*, *turn*, *raise*, *squeeze*, and *shake*. Participants were not informed any of these behaviors beforehand. All participants experienced all six behaviors; the order of behaviors was counterbalanced across participants.

We gave participants two minutes to explore each behavior and encouraged them to think aloud. Participants then described “what they felt the cube wanted them to do” and

rated how confident they were about this judgment on a 7-item Likert scale. We videotaped participant's responses.



**Figure 15: Four participants exploring (a,b) *repel* and (c,d) *raise***

## Apparatus

We used the prototype described earlier to actuate users using EMS, but replaced optical tracking by a Wizard-of-Oz approach. Hence, the wizard visually confirmed the user's contact/approach with/to the object and triggered the predefined stimulation as defined in each trial (i.e., the behavior for that trial). This allowed us to avoid the use of markers, which we felt would have biased the study by suggesting grasping poses. It also guaranteed perfect "tracking".

Calibration of each pose took about 2 to 5 minutes and was conducted by the experimenter. There was no re-calibration during trials.

## Experimental design

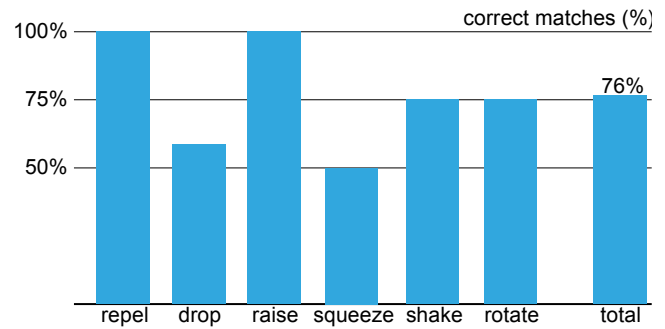
In order to prevent Task 2 from biasing the outcome of Task 1 (by providing additional context for the observed behaviors), we forewent counterbalancing and had all participants perform Task 1 first, then Task 2. The duration of each task was around 20 minutes (minus calibration time).

## Participants

We recruited 12 participants (2 female, 10 male) from our institution (*mean*=25 years old, *SD*=3.36). All were right handed. Participants received a small compensation for their time.

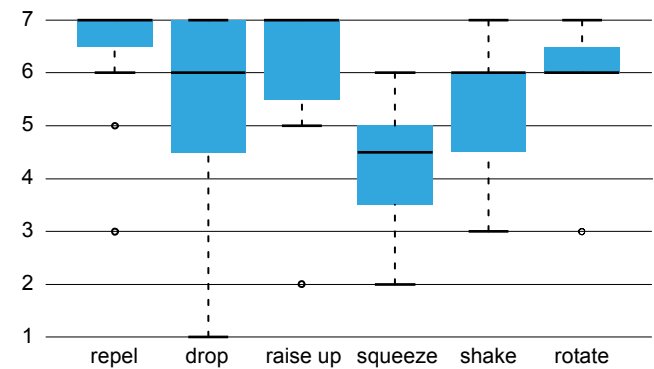
## Results

Overall, in 76% of all trials participants correctly named the behaviors the object had been designed to communicate. Figure 16 breaks down the results by individual behavior. In the remaining 24% of trials where participants did not name the exact behavior, they named some behaviors that were reasonably close, such as *juggle* instead of *shake*. Overall, this result suggests that affordance++ indeed allowed the blank cube to communicate identifiable object behaviors.



**Figure 16: Correctly guessed behaviors, average for all users.**

The most successful behaviors were *repel* and *raise* in that all participants correctly named them. These behaviors were also rated very high on confidence, as shown in Figure 17. Participants came up with the correct answer for *repel*, sometimes instantly when they first approached the object, as depicted in Figure 15. Six participants stated: "it does not want to be touched" one "I cannot touch it" and one "I'm not allowed to touch it".



**Figure 17: Confidence per behavior (Median and IQR, and total range of variation).**

*Raise* was equally well understood by participants, however it often took additional exploration: "It wants to be lifted to my face, perhaps for eating" (6 participants), "throw it away" (P2), or "look closer" (5 participants). Two participants added that "raise" should elicit more muscles, such as the shoulder muscles for increased realism.

*Shake* and *rotate* (Figure 18) were matched correctly in 75% of the trials, and were found to be understandable. Likewise, as for *repel*, we observed *shake* to be fairly quickly recognized, as most participants provided an answer within the few first seconds: "it moves me back and forth, like shaking" (P4) or "it's shaking" (P2).



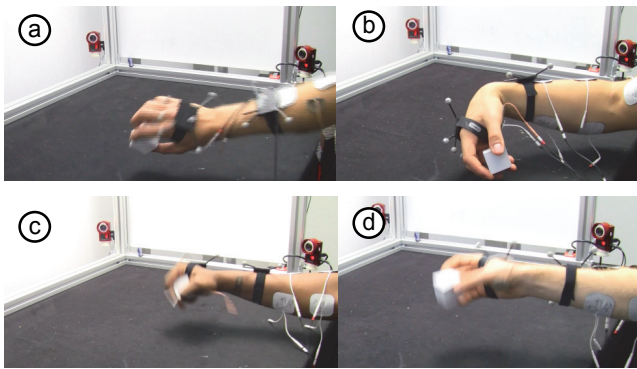


Figure 18: Four participants exploring (a,b) *shake* and (c,d) *rotate*. (b) *Rotate* failed because the wrist flexed more than it turned.

*Drop* and *squeeze* (Figure 19) were found to be misleading, being guessed for 58% and 50% of the cases, respectively. Squeeze was rated less understandable than all other behaviors. The participants described most mismatches with regards to *squeeze* as: “a bit of turning” (P1), “a slight twist” (P3) or “rotating the cube in the palm using the fingers” (P9). As correct guesses we classified “to squeeze it” (P2, P4, P10), “grab harder” (P5), and “hold with more pressure” (P12). Analysis of our video recordings revealed that four participants’ *squeeze* pose was also characterized by some degree of wrist turning, caused by the palm flexor, which might explain the confusion.

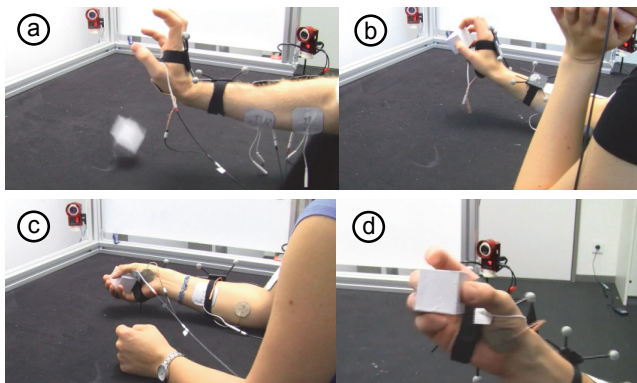


Figure 19: Four participants exploring (a, b) *drop* and (c, d) *squeeze*. (b) Here the muscle actuation was not sufficient to cause the participant to drop the object.

However, *drop* was still rated as understandable, because even if the cube did not properly fall from the closed grasp, the motion was found to still convey that the cube “did not want to be lifted” (P7) or “thrown like a dart” (P12). The correct matches we described as: “to let it fall” (P3, P2).

### Task 2: affordance++ communicating use

The goal of this task was to verify that affordance++ indeed allows objects to communicate use. We had participants operate six objects that tried to communicate their non-obvious use using affordance++. In particular, we wanted to assess whether affordance++ is able to communicate the three categories of behavior mentioned earlier, i.e., motion, multi-step processes, and dynamically changing behaviors.

Figure 20 shows the six objects used for each of the six trials. These are the six objects discussed earlier. They included three unfamiliar tools, i.e., avocado peeler with avocado, nail sweeper with nails, and designer lamp. All participants confirmed that they were unfamiliar with these objects. Next were three familiar objects that we had provided with new behavior, i.e., a door handle that opened to the left, a cup filled with hot liquid, and a spray can that required shaking before use.



Figure 20: The objects used in Task 2

### Procedure

For each trial, we placed one of the six objects on the table in front of them (to prevent them from watching the setup, we blindfolded them until ready). We then asked participants to “prepare the avocado for eating in thin slices” (avocado tool), “place all nails into the container” (nail sweeper), “turn the light on” (lamp), “drink some water” (cup), “open the door” (door), and “paint this” (spray can). We encouraged participants to think aloud while interacting.

Once the participant had completed the task, we asked: “please explain step by step what the object did to you.” Note that the name of the object was never stated; we simply referred to it as “object”. Participants also self-assessed how well they had understood the suggested use on a 7-item Likert scale, how much they felt that the object *itself* (i.e., without the actuation) had communicated its use (7-item Likert), and how much affordance++ had helped them discover the use of each tool for each trial (7-item Likert).

### Results

Each of the twelve participants successfully figured out how to operate each of the six objects. We organize the results below accordingly to the three key features of affordance++: (1) motion, (2) multi-step processes, and (3) behaviors that change over time.

#### (1) Affordance++ communicates motion

All 12 participants, for example, shook the spray can. Ten of them stated that they had shaken the can because of the actuation and they would otherwise have forgotten to do so. One of the participants who stated to have not forgotten to shake added: “I found it useful that the system shakes the can for me, as a way of confirming what I was about to do, I might forget some other time, but this time I did not” (P4). For the majority of participants that would have forgotten to shake, the first reactions were enthusiastic: “cool, I was about to forget” (P1). As shown in Figure 21, all participants

agreed that the spray can itself had not (visually) conveyed the requirement to shake, but that they had understood the shaking motions. Lastly—probably in the light of their forgetfulness—participants rated *affordance++* to be useful in this case.

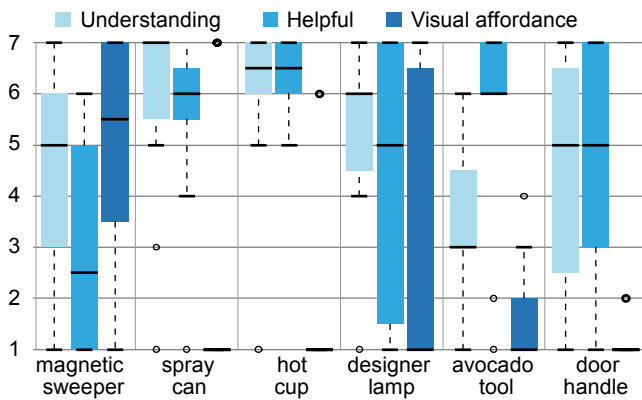


Figure 21: Participants' ratings for the six test objects

Ten of the participants stated to have figured out how to turn the designer lamp on based on the induced motion. Comments included “this helps me very much, I had no idea” (P2), “(...) my intention would have been to push it like a button, but I couldn't find a button” (P9). The other two participants discovered the tilting mechanism accidentally by repositioning the lamp in all possible configurations or by mere chance. While most users rated the lamp's visual affordance as poor, two users rated it as 7 (i.e., easy to visually assess tilting) and added: “tilting was my first intuition, but by moving my muscles it confirmed it” (P3).

### (2) *Affordance++ communicates multi-step processes*

All participants explored the avocado tool before touching the avocado. While reaching for the knife blade they got repelled, the actuation was suggesting them to grasp the other end. Then, *affordance++* shook the wrist up and down to suggest a cutting motion, P3 stated: “I've seen this before, it means chop” and P7 said “I was confused, but then I got confident that it was a knife because of the gesture.”

After participants had sliced the avocado in half, five of them released the knife by opening the grasp slightly and explored an alternative way to remove the pit. Five of them stated that the actuation had suggested doing so. These participants were fairly surprised when they realized that they needed to push the hole against the pit, which *affordance++* had suggested by shaking the tool up and down: “when I put it on the pit it told me to push. It repelled [my hand] when I tried to use the blade” (P11), “I would have used the knife, but not the rest” (P6) and “It really helped me to use this tool because I had no idea [how to use it]” (P2).

All participants tried to peel the avocado using the knife, but were repelled by *affordance++*. After that, *affordance++* opened the grasp to suggest that the tool should be manipulated in a different way. All participants responded accordingly and explored an alternative way to hold the tool, such as “normally I do it with a spoon, but it didn't want me to cut it, which made me turn it and explore the tool, and then

I saw [the blades] and felt how to use it” (P7), “The scooping tool told me to pull [points down towards the avocado]” (P11). Mainly due to the pit removal step, e.g., “all [the steps] worked out except this part in the middle, it really confused me” (P10), participants on average rated their own understanding of the actuation lower than for the other tasks (see Figure 21). Still, participants felt *affordance++* was helpful with regards to the avocado tool. Moreover, all participants agreed that their first visual exploration did not reveal how to use the tool.

Lastly, the magnetic sweeper was the task in which participants rated the necessity for *affordance++* lowest. This is likely explained by the fact that participants stated that the object *itself* already visually conveyed how to use it (see Figure 21), i.e., “looks like a magnet” (four participants). Furthermore, although they understood the stimuli during this task, they did not feel the need for *affordance++* to collect all screws correctly.

Also, four participants found that the system corrected the order of the task: “first I wanted to touch the lower handle (...) I got repelled (...) and then it helped me (...) to grasp the upper one”. Furthermore, some participants assumed pulling the lower handle would collect the screws, which is incorrect because pulling the lower handle releases the magnet. When they did so, *affordance++* repelled them from pulling it and they responded accordingly: “first thing [I did] was pulling it, the system pulled my hand [away] to prevent that. It was very clear and very helpful” (P8).

### (3) *Affordance++ provides dynamic affordance according to state*

During the “drink some water” task, 11 out of 12 participants reached first for the cup's body. They felt repelled from grasping the cup's body and proceeded to the handle after some seconds. One participant added “it doesn't want me to not drink from it” (P10). Furthermore, another participant confirmed that the water was hot by attempting to dip the finger in the liquid, *affordance++* repelled again and the participant stated “ah! I feel the heat now” (P7). The *affordance++* poses used for this task, i.e., repel from body and grasp around handle, were found understandable by the participants (see Figure 21). All participants agreed that the cup did not provide a visual cue that it was hot. Participants were enthusiastic about how helpful *affordance++* was for this situation and most added: “for hot liquids or any danger, is very helpful”.

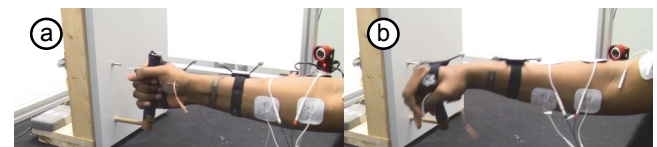


Figure 22: Example of overriding the conventional behavior. (a) As participants expected this door to open to the conventional side, they turned the handle right. (b) *Affordance++* induced a left turning motion instead.

The door handle worked in 9 out of 12 cases. Even with the non-standard turning direction (left instead of right) participants opened the door without forcing it right or pulling it:



“I turned the lever to the left side. It’s not the normal direction” (P1), “It clearly gave me a direction to turn. (...) I would have tried around more stuff” (P4), and “I first tried in one way, and it pushed me to the other direction” (P12). Furthermore, all participants agreed that the door handle did not visually communicate to which side it would open. Lastly, participants found the system to be useful such as “if I would travel [to another culture] and find such a door, it would be helpful” (P12).

## RELATED WORK

The work proposed builds on the theoretical foundations of affordance, animated objects, and haptic actuation of users.

### Affordance

Affordance is a ground concept in HCI, thus much theoretical background can be evoked to explain it. Gibson was one of the earliest to seek a formal definition: “affordances (...) are what it offers, what it provides or furnishes” [7]. His definition roots affordance in the object’s ability of offering or providing use for the user. Digging deeper, his definition of affordance elicits the visual channel as the main channel for a perceived affordance [7].

Affordance, however, has been revisited and refined numerous times, most notably by Norman [4]: “affordances define what actions are possible” and “affordances are relationships between object and user”. Norman restricted affordance to the domain of physical objects, “affordances make sense for interacting with physical objects, but they are confusing when dealing with virtual ones”.

Interestingly, the first theorists of affordance had already unfolded its intrinsically dynamic nature, i.e., the affordance of an object is not static in time. Gibson provides an example: “(...) a middle-sized metallic object affords grasping, but also conducting electricity” [7]. McGrenere and Ho go further by examining the often-ambiguous nature of objects’ affordances, state the limitations of current affordances due to their static nature: “an affordance does not change as the needs and goals of the actor change” [16].

### Animated Objects

The closest concept to our proposal is animated mechanical objects, some of which can be found in everyday life, such as automated doors or blinds and cleaning robots [6]. A notable example is Tocky [24], an actuated alarm clock, which is able to express different behaviors, such as running away from the user to stimulate faster wake up.

In research, Djajadiningrat et al. discuss how animating every-day objects provides the missing time component, showing “physical movement as a carrier of meaning” and pointing out that human-product interaction has long neglected “motion” and “time” as a quality of objects around us [3]. Petersen et al. applied animations to a curved display surface and found that users attribute meanings to the different states, including when the devices animates while a hand approaches [19]. Kwak et al. observed participants’ responses to shape changing objects and concluded that dynamic motion is attributed with meaning; e.g., changes during the approach phase are seen as “caution” [12].

The “Thrifty Faucet” [25] engages into dialogs—through motion—with the user. The actuation provides it with a dynamic nature, allowing the object to express three behaviors: seeking, curiosity, and rejection (repelling the user from usage). coMotion is an actuated bench, which can dynamically change its shape [8]—depicting this motion turned out to be one of its primary advantages [21].

The Actuated Workbench is a device that uses magnetic forces to move metallic objects on a table in two dimensions, for example to notify the user [18]. Similar approaches using ultrasound [15], allow displacing non-metallic objects, but are limited to objects of a few grams and cannot actuate objects while the user grasps them.

Shape displays form dynamic physical surfaces, thus can vary their affordance. However, these are highly engineered abstract objects and not every-day household items. An example is *inFORM* [5], a physically actuated pin-display, which allows for direct manipulation with virtual (projected) objects. Moreover, it provides means to actuate everyday objects: moving a tablet, a ball, and so forth. However, its actuation relies on a stationary infrastructure, restricted to the tabletop form factor.

### Haptic Actuating of Users

Most haptic systems administer forces to the user’s body using pulleys [17] or exoskeletons [26]. An example of a pulley system is SPIDAR [17], which displaces the fingertip by pulling. Exoskeletons such as the FlexTensor [26] require an external apparatus to be mounted on the user. While these approaches deliver high precision, for example in haptic simulators, they do not allow for mobile use [14].

In contrast, electrical muscle stimulation (EMS), a technique rooted in the field of medical rehabilitation [22], allows for unencumbered actuation while mobile [14]. EMS uses electrical impulses to trigger involuntary muscle contractions, which then animate the user’s muscles [11]. The *Possessed Hand* [23] controls the user’s fingers to support learning tasks, such as playing a new instrument. This is an example of extending the affordance of an object (the musical instrument) by means of actuating the user’s muscles.

## CONCLUSIONS AND FUTURE WORK

In this paper, we presented the concept of *affordance++*, i.e., an extension to the traditional notion of affordance that allows objects to also communicate (1) motion, (2) multi-step processes, and (3) behaviors that change over time. *Affordance++* achieves this by actuating users, rather than the objects. This way, *affordance++* enables walk-up use.

Interestingly, because we actuated the user’s muscles instead of actuating the object, we expected users to perceive that they were the ones depicting the usage instructions. However, this is not what we observed in the user study. In fact, we observed that the agency (“who did what”) was redirected to the object—“it doesn’t want me to not drink from it” (P10) is very different from “I should not drink from this cup”. The latter would elicit a more user-centered (or ego-centered, the “I”) understanding of affordance, rooted in “what can I do with this object”. However, it seems that we

observed, more often, the former. This projects the affordance to an object-centered perspective (the “it”). Furthermore, the aforementioned observations reported in Task 1 suggest that, to some extent, users “believe” that a script with an intention is attached to the object. For instance, six participants stated the cube “wants to be lifted to my face, perhaps for eating”. This ties together with the notion, developed by Latour, that humans communicate with the artifacts they operate [13]. Indeed, Verbeek states: “technological artifacts are able to exert influence on human actions, by means of non-lingual message” [27]. Comments such as “the tool *told* me to pull” (P11) suggest this is the case for affordance++, in which object-user dialogs do not happen on a verbal level (visual or auditory) but non-verbally, through the user's body motion.

It remains to be understood, for future work, whether another user actuation technique or even animating the objects themselves via mechanics, would shift this object-centered perspective to a different experience.

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